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This report describes a two-year research effort directed toward the understanding of very robust fiber lasers utilizing Yb:Er co-doped fiber for the gain medium. We have achieved stable CW output utilizing in-fiber Bragg grating technology. Of the greatest importance is the effectiveness of Yb:Er co-doped fibers for the purpose of suppressing ion-pair induced Q-switching and for the enhancement of pumping in high gain fibers.

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ALL FIBER BASED OPTICAL TRANSMITTERS AND SWITCHING TECHNOLOGIES

FINAL TECHNICAL REPORT

TO

DARPA/AFOSR

BY

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PROJECT PERIOD: 7/1/95 - 9/30/97

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INTRODUCTION

Diode laser pumped fiber lasers with in-fiber Bragg gratings have a very simple laser structure, which makes them very attractive for optical fiber communication system applications. Among them, short cavity length, single mode Er-doped fiber lasers can yield CW output power at multi-milli watts with a single frequency oscillation (Ref. 1,2,3). However, the output of single frequency fiber lasers often exhibits self-pulsation (Ref. 4) caused by ion-pair induced perturbations or instabilities caused by pumping fluctuation at laser relaxation oscillation (Ref. 5,6). Using an optoelectronic feedback circuit the relative intensity noise (RIN) can be reduced by as much as 30 dB (Ref. 7). However, the use of a feedback loop makes the laser system more complicated and costly, therefore less attractive for practical applications.

This report describes a two-year research effort directed toward the understanding of very robust fiber lasers utilizing Yb:Er co-doped fiber for the gain medium. We have achieved stable CW output utilizing in-fiber Bragg grating technology. Of the greatest importance is the effectiveness of Yb:Er co-doped fibers for the purpose of suppressing ion-pair induced Q-switching and for the enhancement of pumping in high gain fibers.

Presently, the only viable candidate as the optical source for TDM/WDM fiber systems for high speed data bus, multi-media video transmission and telecommunications network is the DFB semiconductor laser. However, frequency drifts and time jitters encountered with DFB semiconductor laser diodes due to thermal, injection current and acoustic effects are hindering the practical implementation of cost effective optical TDM/WDM fiber systems. For analog multi-media cable TV networks, semiconductor diode lasers do not have the required linearity or dynamic range. For these systems, optically pumped solid-state lasers with a well-developed Li b NO_3 waveguide modulator is the only choice and is being deployed presently. Single mode fiber lasers, on the other hand, are perfectly compatible with fiber transmission channel, implying that nearly 100 percent laser power can be coupled into the fiber transmission line. These lasers have very pure spectral characteristics governed by the in-fiber Bragg gratings and are inherently much more immune to thermal, acoustic and electrical effects than injection semiconductor lasers. Fiber lasers are more optically pumped by diode lasers. Because diode lasers are used only as the pump source, spectral purity is not an issue. By using Yb:Er codoped fiber, the pump laser wavelength can be chosen over a range from 810 nm to 980 nm. By choosing a pump wavelength in the 800 nm region, a significant cost-saving can be obtained because high-power AlGaAs diode lasers are more readily available at low cost than those made of InGaAs. Therefore, diode pumped fiber lasers, if successfully developed, can offer many advantages over the DFB semiconductor lasers in terms of stability, spectral purity as well as beam quality and cost.

This report summarizes the work performed under the DARPA/AFOSR sponsored program starting by demonstrating a single-frequency Er-doped fiber laser [Ref. 2, 3] and subsequently by demonstrating the mode-locked operation of fiber lasers [Ref. 12, 13]. Recently, we have performed a detailed analysis of the Er-doped fiber lasers by solving the rate equations involving various energy transfer processes in Er ions and Yb:Er ions and including photon fluctuation in the pump [Ref. 6,7]. We showed that Yb:ions not only can increase the effective pumping rate significantly but also can suppress the self-pulsing problem. Therefore, we believe that by a proper design, it is possible to obtain low noise and stable laser output at low as well as at high power level from a Yb:Er codoped fiber laser emitting at the eye-safe wavelength with a reasonable efficiency in power transfer. Furthermore, Yb ions have a much wider absorption band that Er ions, therefore the Yb codoping can relax the requirement of the wavelength accuracy of pump sources and allow the use of low-cost high-power diode arrays for pumping Er-doped fiber lasers. This is an important consideration for developing low-cost, low-noise, high-power Er-doped fiber lasers.

In the following section we present a detailed stability analysis of Er-doped and Yb:Er codoped fiber lasers and introduce ways to suppress the instabilities occurring in these lasers, hence to achieve stable operation desirable for broadband communication system applications.

2. A Stability Analysis

2.1 Relaxation Oscillation

We first present our analysis on the power fluctuation in fiber lasers caused by resonant diode pump power perturbation. We show that this fluctuation is inversely proportional to photon life time (Ref. 6). We also show that such instability caused by resonant pumping perturbation can be suppressed by using high-gain fibers. By solving the rate equations (Ref. 6) involving the upper laser level population density and photon density q_0, we obtain a simple (approximate) expression for photon fluctuation function q_m as given by

$$\frac{q_m}{q_0} = \frac{1}{\omega_m \tau_c} \frac{R_m}{R_{p0}} \tag{1}$$

where the oscillation frequency ω_m is given by

$$\omega_m = \sqrt{R_{p0} N_0 r_q} \tag{2}$$

R_0 and R_m are unperturbed and perturbed pump rates, respectively. $r_q = c\sigma_2/n$ where σ_2 is the absorption cross section. τ_c is the photon cavity lifetime. N_0 is Er doping concentration which is about $3\times10^{19}/cm^3$. Figure 1 shows the variation of relative fluctuation of photon density as a function of τ_c. The solid curve is the result obtained from the approximate expression (1). The square points are the results obtained by solving the rate equations numerically. We see that the approximation is valid for $\tau_c \geq 4$ nsec. As an example, for R_m/R_0= 0.5% and τ_c =4 nsec, a 30% photon density fluctuation is expected. Equations (1) and (2) indicate that the photon density fluctuation can be significantly suppressed by using a Er-doped fiber with a high-gain coefficient or high Er-doping concentration N_0. However, the use of high gain Er-doping fibers leads to a different set of problems. In particular, the self-pulsing instability due to ion-pair interactions becomes the dominant problem.

2.2 Ion-Pair Induced Self-Pulsing

We found that the ion-pair induced self-pulsing in Er-doped fiber lasers depends largely on the ratio γ of emission to absorption cross sections. Because of this dependence, self-pulsing can be suppressed by increasing the γ value. To treat this problem analytically, we solve the rate equations by using the model introduced by Sanchez and co-workers (Ref. 8). In this model, Er-ions are separated into two groups: isolated ions and ion-pairs. Isolated ions can be described by a two-level system, whereas the ion-pairs are described by a three-level system, which is comprised of the ground state n_1, one-ion excited state n_2, and an ion-pair excited state n_{ij}, (both ions excited). Coupled with the population of these three levels is the photon density, q. The laser dynamics are described by four coupled rate equations as given by (Ref. 9)

$$\frac{dn_2}{dt} = R_p(1-n_2) - qr_q[(\gamma+1)n_2 - 1] - \frac{n_2}{\tau_2} \tag{3}$$

$$\frac{dn_{11}}{dt} = -R_p n_{11} + q\alpha r_q[\gamma - (\gamma+1)n_{11} - \gamma n_{22}] + \frac{1-n_{11}-n_{22}}{\tau_2} \tag{4}$$

$$\frac{dn_{22}}{dt} = R_p(1-n_{11}-n_{22}) - q\alpha r_q[n_{11} + (\gamma+1)n_{22} - 1] - \frac{n_{22}}{\tau_{22}} \tag{5}$$

$$\frac{dq}{dt} = qr_q N_0\{(1-2x)[(\gamma+1)n_2 - 1] + \alpha x(\gamma - 1 - \gamma n_{11} + n_{22})\} - \frac{q}{\tau_c} \tag{6}$$

where

$$R_p = \frac{P_p}{h\nu_p A_{eff}}\sigma_p, \qquad r_q = \frac{c}{n}\sigma_a. \tag{7}$$

From (3) to (6) we obtain a set of steady-state solutions. The stability conditions can be determined by solving the eigen-values of the matrix [A] formed by a set of homogenous equations derived from (3) to (6).

For laser parameters above threshold, matrix [A] always has two real negative eigen-values and a pair of complex conjugate eigen-values, whose real part determines the stability of the laser. But when the real part is positive, any perturbation will increase with time exponentially and lead to unstable operation involving self-pulsing.

Fig. 2 and 3 give the calculated stability diagrams on the x-Pp plane. Fig. 2 shows the dependence of laser stability on ion concentration N_0 and γ with a fixed photon life time τ_c =10 n sec. Fig. 3 shows the dependence of photon life time and γ with a fixed $N_0 = 8\times10^{18}\ cm^{-3}$. In all cases, when γ is increased from 1 to 1.5, the unstable area i.e. the pump power required to suppress self-pulsing is decreased by half or more for a given N_0 and τ_c. The calculated results are in good agreement with our experimental observations from two fiber lasers, one operating at λ = 1.531 um (γ = 1) and the other operating at λ = 1.56 um (γ=1.5). Er-doped fiber in these cases has a N_0 value equal to $3.6\times10^{19}\ cm^{-3}$ corresponding to a gain coefficient of 55 dB/m. at 1.53 um.

2.3 Effects of Yb:Er Co-Doping

In Section 2.2, we show that ion-pair induced self-pulsing can be suppressed by increasing the emission to absorption cross section ratio of Er-ions. This approach has very limited usefulness because γ values cannot be increased freely. Another approach is to increase the pump rate to bleach the ion-pair effect. However, this is limited by the available diode laser pump power. To increase the pump efficiency, it has been demonstrated (Ref. 10) that the use of Yb:Er co-doped fiber can be very effective.

We have analyzed the Yb:Er system and derived a functional dependence of the effective pumping rate of Yb:Er co-doped fibers on fractional Er ion concentrations. We show that the Yb:Er co-doped fiber is very effective to suppress the ion-pair induced self-pulsing in Er doped fiber lasers. To investigate the effects of Yb on Er ions, we assume that Yb ion concentration is high enough to satisfy the fast diffusion limit, so that rate equations can be used to describe the energy transferring process. Using the same model (Ref. 8), we introduce one additional coupled rate equation for the Yb excited state population density as given by

$$\frac{dM_2}{dt} = R_p^{Yb}(M_0 - 2M_2) - \rho M_2 N_0[(1-2x)(1-n_2) + x(1-n_{22})] - \frac{M_2}{\tau_{Yb}} \quad (8)$$

Where M_1 and M_2 are the ground state and the excited state of Yb ion densities, respectively, and

$$R_p^{Yb} = \frac{P_p}{h\nu_p A_{eff}} \sigma^{Yb}, \qquad R_p^{Er} = \frac{P_p}{h\nu_p A_{eff}} \sigma_p, \qquad r_q = \frac{c}{n} \sigma_a. \tag{9}$$

The laser dynamic behavior can now be described by coupled rate equations with a slight modification of (3) (4) and (5) by replacing R_p by $R_p^{Er} + \rho M_2$ to include the effect of Yb ions. For the steady state laser operation, the calculated effective pump rates for different Yb codoping concentration at λ pump=980nm are shown in Fig. 4. Results show that the enhancement of the pump rate by Yb ions becomes more effective when the pump power is relatively low. This fact is important for suppressing the ion-pair induced self-pulsing in Er-doped fiber lasers because the self-pulsing usually occurs at low to medium pump power level.

From a set of steady-state solutions, we obtain the stability conditions by solving the eigen-values of a new [A] matrix using the nominal values for all the parameters of Yb:Er codoped fibers and taking $\gamma = 1$ (the worst case). Fig. 5 shows the calculated stability diagrams on the x-Pp plane for different Yb:Er codoping concentrations, while keeping the same Er doping concentration. We see that for Yb:Er = 9: 1, the pump power required to suppress the self-pulsing for an ion-pair fraction of 30% is about 3mW, which is only 1/50 of the required power for the same ion-pair fraction without Yb codoping.

In summary, we have investigated the laser noises and instabilities in Er-doped and Yb:Er codoped fiber lasers. We showed that a small fluctuation in the pump laser power can lead to very large fluctuation in output laser power at relaxation oscillation frequency. Our results indicated that this instability can be suppressed by using high gain Er-doped fibers. However, with high-gain fibers, Q-switching or ion-pair induced self pulsing occurs, especially at low and medium laser pump power levels. This instability can be reduced by shifting the operating laser wavelength from the peak of the absorption at λ =1.535 um to high wavelengths. An alternative approach is to codope the fiber with Yb ions at very high concentration level to suppress the ion-pair-induced self-pulsing. By doing so it is possible to use high-gain or highly concentrated Er doped fibers for lasing media. Because of the very efficient energy transfer process that exists between Yb and Er, the introduction of Yb can significantly increase the pumping rate. As a result, ion-pair induced self pulsing in Er-fiber can be suppressed at relatively low diode laser pump power level. From the results of these analyses, we can establish useful scaling models for stable operation of cw fiber lasers.

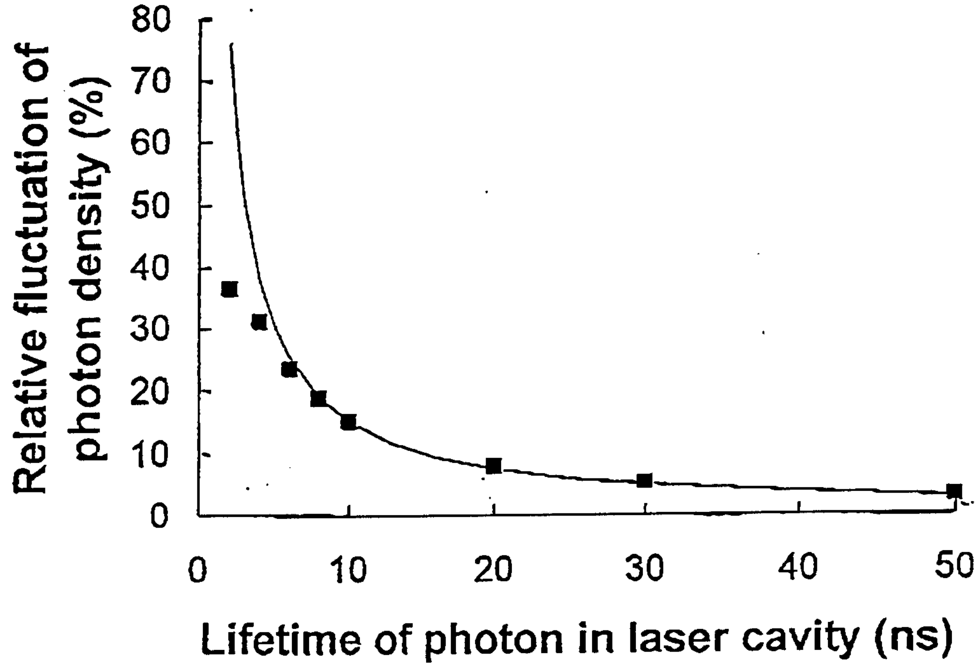

Fig. 1 Photon density fluctuation vs. photon lifetime.

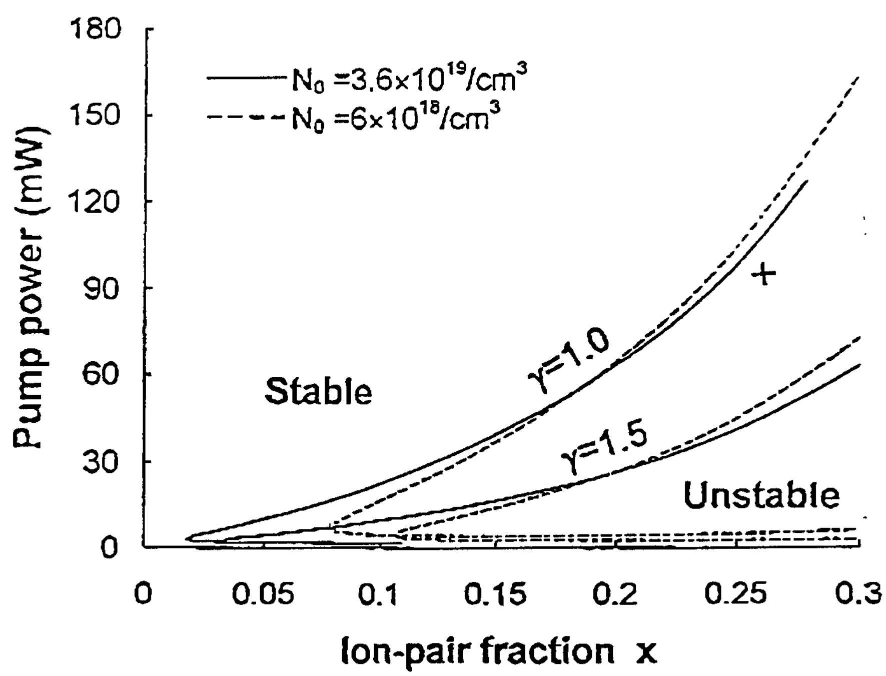

Fig. 2 Stability diagrams for various σ_a nd γ values but at a fixed τ_c= 10 n sec as a function of ion-pair fraction.

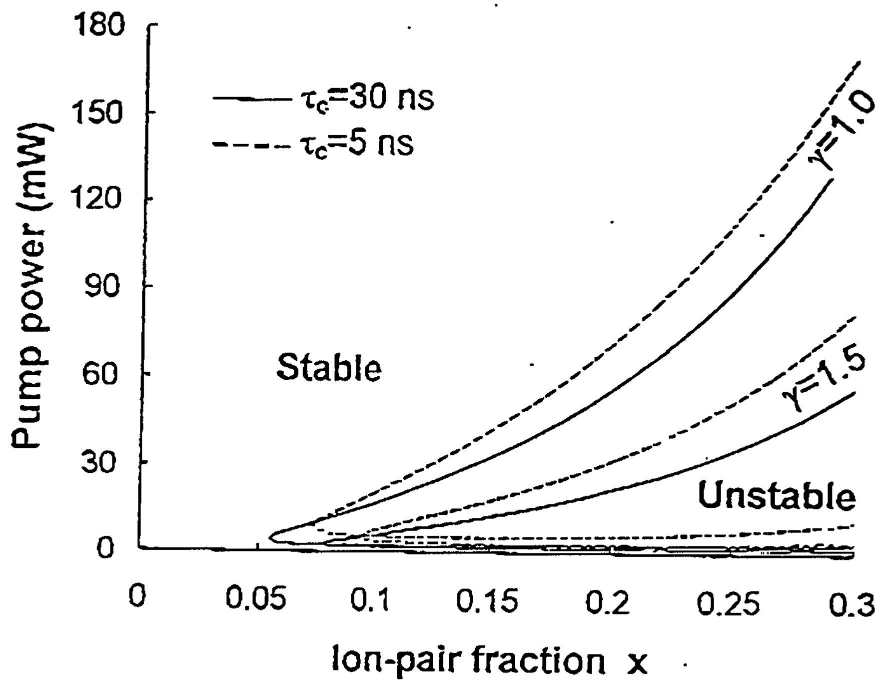

Fig. 3 Stability diagram for various σ_8, τ_c and γ values as a function of ion-pair fraction.

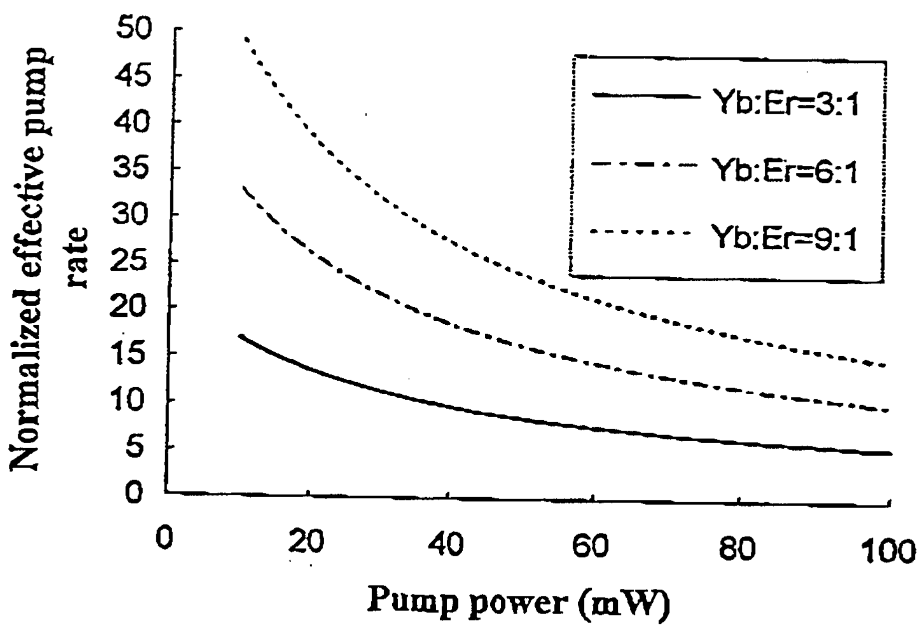

Fig. 4 Effective pump rate for various Yb:Er doping concentration ratios.

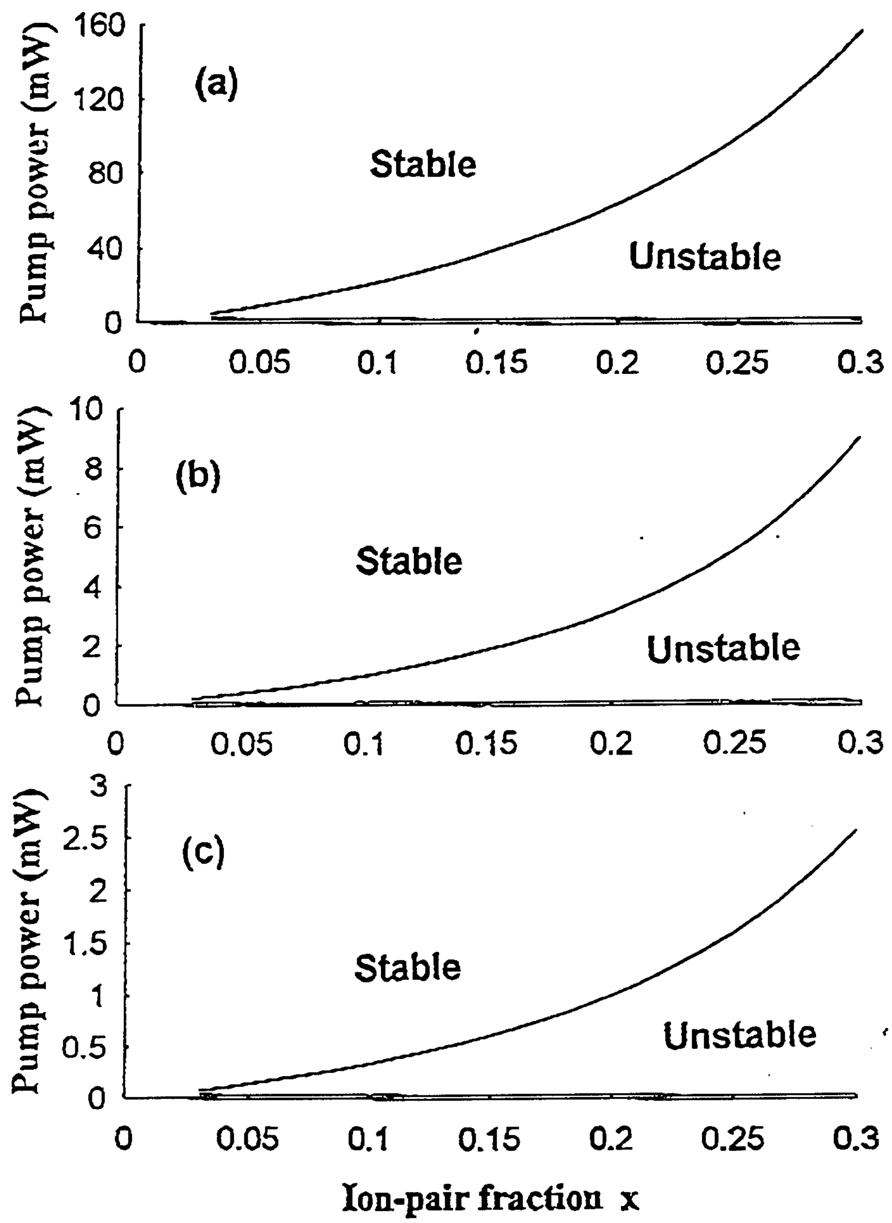

Fig. 5 Stability diagram for various Yb:Er doping concentration rations =
(a) Yb:Er = 0 (b) Yb:Er = 3:1 and (c) Yb:Er = 9:1

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